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Search for Exotic Couplings in Neutron Decay: A Measurement of the Transverse Polarization of Electrons

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Abstract

First results are presented from an experiment that aims at the simultaneous determination of both transversal polarization components of electrons emitted in the decay of free neutrons – two observables that have never before been addressed experimentally. They reveal first-order sensitivity to real and imaginary parts of the exotic scalar and tensor interactions.

Key words: Standard Model, exotic couplings, time reversal violation, neutron-decay, neutron polarization, electron polarization
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The Standard Model (SM) predictions of T-violation originating from the quark mixing scheme, for systems consisting of u and d quarks, are 5 to 10 orders of magnitude lower [1] than the experimental accuracies available to date. This applies to determinations of the T-violating electric dipole moments as well as to T-violating correlations in decay or scattering processes. With such a strong suppression these experiments provide a large window to search for physics beyond the Standard Model. It is a general presumption that

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time reversal violation phenomena are caused by a tiny admixture of exotic interaction terms. Therefore, weak decays provide a favorable testing ground in the search for such feeble forces. Mixed beta transitions like neutron decay provide a direct access to the weak scalar and tensor interactions that are not present in the SM. Physics with very slow, polarized neutrons has a great potential in this respect. The experiment presented here measures two observables, the R and N correlations, that have not been so far addressed experimentally in neutron decay.

The electron polarization appears in several terms of the famous decay rate formula [2]. Most directly the longitudinal and two transversal components of this polarization can be recognized in the terms that are scaled by the correlation coefficients G, R and N, respectively. These can be expressed in terms of the weak interaction coupling constants C_i, C_i', where i stays for V (vector), A (axial vector), S (scalar) and T (tensor) interaction, as shown in Ref. [2]. Applying the SM assumptions: $C_V = C_V' = \Re(C_V) = 1, \quad C_A = C_A' = \Re(C_A)$, neglecting the terms quadratic in C_S, C_S', C_T and C_T', substituting the neutron decay matrix elements $M_F = 1$, $M_{GT} = \sqrt{3}$ and defining $\lambda = C_A/C_V$ one obtains

$$\begin{aligned} G &= -1 + \frac{1}{137}\cdot\frac{m}{p_e}\cdot\frac{1}{1+3\lambda^2}\left[\Im\left(\frac{C_S+C_S'}{C_V}\right) + \lambda^2\Im\left(\frac{C_T+C_T'}{C_A}\right)\right], \\ R &= \frac{\lambda}{1+3\lambda^2}\left[\Im\left(\frac{C_S+C_S'}{C_V}\right) + (2\lambda+1)\Im\left(\frac{C_T+C_T'}{C_A}\right)\right] + \frac{1}{137}\cdot\frac{m}{p_e}\cdot\frac{2\lambda(\lambda+1)}{1+3\lambda^2}, \\ N &= \frac{\lambda}{1+3\lambda^2}\left[\Re\left(\frac{C_S+C_S'}{C_V}\right) + (2\lambda+1)\Re\left(\frac{C_T+C_T'}{C_A}\right)\right] + \frac{m}{E_e}\cdot\frac{2\lambda(\lambda+1)}{1+3\lambda^2}, \end{aligned} \quad (1)$$

where m, E_e and p_e are the electron mass, energy and momentum, respectively. From Eqn. 1 it is clear that the N and R coefficients are well suited for direct searches of physics beyond the SM, provided the final state interaction effects (FSI) that are represented by the rightmost terms in the above expressions are well under control. The energy averaged value of the FSI contribution to the R coefficient is ≈ 0.001 and beyond the precision of the current experiment while a ≈ 0.07 large electromagnetic correction in the N correlation is measurable and can be used for a direct sensitivity check of the apparatus.

The R and N correlation coefficients can be inferred from two components of the electron polarization: R is proportional to the component perpendicular to the decay plane (spanned by the neutron spin and the electron momentum vectors) while N scales the component parallel to that plane.

Mott scattering from high Z nuclei is an ideal polarization analyzer for low energy electrons. The sensitivity to the electron spin is provided by the spin-orbit force emerging from the parity and time reversal conserving electromagnetic interaction and thus is strictly limited to its transverse components. For energies below 1 MeV the analyzing power of the Mott scattering from Pb nuclei reaches -0.5 at backward angles [3].

The experiment was performed at the Paul Scherrer Institute, Villigen, Switzerland. The neutron beam from the cold neutron facility FUNSPIN [4] with an intensity of about 10^{10} s^{-1} and the average (vertical) polarization $P_n > 80\%$ was guided to the decay volume. The Mott polarimeter consists of two sets of electron detectors with integrated Pb scattering foils arranged in a planar geometry as sketched in Fig. 1. A detailed description of this device as well as of the data analysis methodology can be found in Ref. [5].

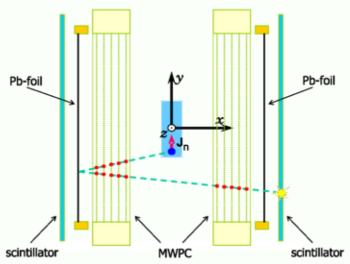

Fig. 1. Scheme of the experimental setup and the measuring principle. The vertical cross section of the Mott-polarimeter is shown. The rectangular area in the middle represents the neutron beam cross section.

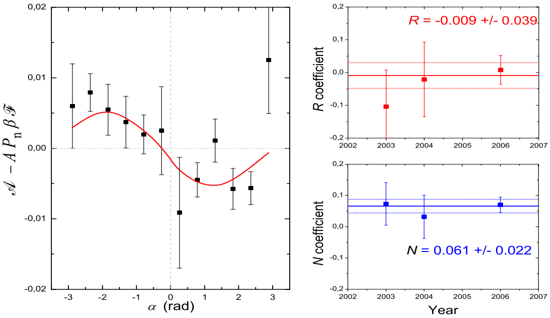

Fig. 2. Left panel: Experimental asymmetry of the Mott scattering with subtracted fake effect induced by an interplay of the decay asymmetry and finite geometry. The solid line represents a two-parameter (N, R) least squares fit to the data sample collected in the 2007 run. Right panel: Experimental values of the N and R coefficients obtained from data sets collected in the runs 2003, 2004 and 2006.

Decay electrons are tracked in low-Z, low-mass multi-wire proportional chambers (MWPC) and are stopped in plastic scintillators. Roughly one out of a thousand electrons undergos backward Mott scattering from a 2 μm thick Pb foil and can be identified by a characteristic "V-track" pattern seen in two projections, c.f. Fig. 1. The requirement that the scattering vertex must be localized on the Pb foil significantly reduces background. The correlation coefficients N and R are extracted from the rate asymmetry $\overline{\mathcal{A}}(\alpha)$ between two properly normalized data sets taken with the neutron spin up (+) and down (−), respectively:

$$\overline{\mathcal{A}}(\alpha) = \frac{\overline{\omega}(+P_n, \alpha) - \overline{\omega}(-P_n, \alpha)}{\overline{\omega}(+P_n, \alpha) + \overline{\omega}(-P_n, \alpha)}, \tag{2}$$

where α is the angle between the Mott scattering plane and the neutron decay plane spanned by the neutron spin and the electron initial momentum vectors. An example of a fit to the data sample collected in the 2007 run is shown in the left panel of Fig. 2. In the right panel, the results from the 2003, 2004 and 2006 data sets are shown. The analysis of all data collected during the 2007 run has not yet been completed. Preliminary results are in agreement with but more precise than those from the 2003, 2004 and 2006 runs and agree with the SM predictions of $N_{SM} = 0.066$, $R_{SM} = 0.001$ within the current precision of about 0.02 - 0.04 (statistical). It has been estimated that the final statistical error should not exceed 0.01.

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